SBRHI-99-2

Rescattering of Vector Meson Daughters in High Energy Heavy Ion Collisions

Stephen C. Johnson*, Barbara V. Jacak, and Axel Drees

The University at Stony Brook, Stony Brook, NY 11794-3800

Abstract

We consider the role of hadronic rescattering of daughter kaons on the observed mass spectra from ϕ meson decays in ultra-relativistic heavy ion collisions. A hadronic cascade code (RQMD v2.4) shows that ∼26% of all ϕ's decaying to K^+K^- in central Pb+Pb collisions at SPS energies ($E_{beam} = 158GeV/A$) have a rescattered or absorbed daughter. This significantly affects the reconstructed invariant mass of the pair and shifts ϕ mesons out of the mass peak. Kaon rescattering depletes the low velocity region, hardening and broadening the observed phi m_t and rapidity distributions respectively, relative to the dilepton channel. This effect produces an apparent change in the experimentally determined branching ratio not necessarily related to chiral symmetry restoration. Comparisons to recent experimental measures at CERN energies reveal a possible mechanism to account for the shape of the observed spectra, though not their absolute relative magnitude.

Typeset using REVTEX

*present address: Lawrence Livermore National Laboratory L-305, Livermore, CA 94550

A. Introduction

Chiral symmetry, the symmetry which acts separately on left- and right-handed fields in QCD, is spontaneously broken in nature, resulting in associated Goldstone bosons in the pion field as well as the observed hadron mass spectra. However, it is expected that the spontaneously broken part of chiral symmetry may be restored at high temperatures and densities [1]. Such conditions might be reached in the interior of neutron stars or during a relativistic heavy ion collision. In fact, a primary goal of high energy nuclear collisions is the creation of such matter and the study of its properties.

One expected signal of the restoration of chiral symmetry is a change of the vector meson properties [1]. In the nuclear system, the self energy of hadrons is changed by the medium they inhabit. A change in the effective mass of daughter particles can change the effective lifetime, and consequently the observed width, of the parent particle that decays in medium. Such modifications could be accompanied by a measureable change in the branching ratio of mesons decaying in the medium. The light vector mesons (ρ, ω, ϕ) offer an especially promising channel for study of chiral symmetry effects due to their multi-channel decays and lifetimes comparable to the space-time extent of the system produced in heavy ion collisions. The ϕ is of particular interest as the sum of the daughter mass of its di-kaon decay channel is very close to the mass of the ϕ. As a result, even a small change in daughter or parent masses could measureably alter the decay channel [2].

Study of vector mesons through their leptonic decay channels, either e^+e^- or $\mu^+\mu^-$ should provide the cleanest signal of the changing masses as leptons interact with the nuclear medium predominantly electromagnetically. In contrast, decays to hadrons are affected by strong final state interactions. If a ϕ decays in the center of the reaction volume in a heavy ion collision, the lifetime of the kaon travelling a distance d through a length L of hadronic matter is $exp(-Ld\sigma)$. Approximating the heavy ion collision as a pion bath with density $d = .5/\mathrm{fm}^3$ and cross section $\sigma = 10 - 100\mathrm{mb}$, the 1/e pathlength of a kaons would be between .2fm and 2fm, much smaller than the size of the collision region. However, while

the hadronic daughters interact in the medium, leptons should escape unscathed.

The rescattering of hadronic daughters in the nuclear medium could mimic or obscure effects of chiral symmetry restoration by causing the reconstructed invariant mass to fall outside the vector meson peak, effectively decreasing the measured yields. While studies of the viability of the di-kaon channel of the ϕ for studying chiral symmetry restoration have been done [2,3], the effect of the rescattering of daughters on the experimentally measured branching ratio has not previously been considered.

B. Model Results

To study the effect of hadronic scattering of daughters, we implemented the hadronic cascade code RQMD version 2.4 to describe the space time distribution of ϕ's and their daughters. In RQMD one can follow the history of all ϕ's that decay throughout the collision along with their daughter kaons. Upon simulation of an event we determine the positions and momenta of all kaons originating from ϕ decays. Fig. 1 shows the invariant mass distribution of all kaon pairs from ϕ decays in simulated central Pb+Pb events at 158 GeV·A/c beam energy. The right hand figures show ϕ's whose daughters escaped from the collision zone without rescattering (top figure) and those whose daughters did rescatter (bottom) yet still escaped the collision zone as kaons. The left hand figure gives an overlay for comparison. Since the ϕ lifetime is comparable to, though larger than, the expected lifetime of a heavy ion collision, most ϕ's do not decay in medium resulting in a tight peak of the invariant mass (M_{inv}) with a width of $\sim$4 MeV. However, $\sim 17\%$ of ϕ's decaying to two kaons have at least one daughter kaon that rescatters and another (non-orthogonal) $\sim 17\%$ of ϕ's have at least one daughter that is absorbed. The sum of these two processes leads to $\sim 26\%$ of decaying ϕ's with an absorbed or rescattered daughter. The M_{inv} distribution of these kaons is much broader than the original distribution; broad enough to escape detection, in particular in experiments with low statistics or large combinatorial backgrounds.

Tables I and II itemize the channels contributing to the first hadronic scattering of a

daughter kaon from a phi meson. The dominant interactions for both K^+ and K^- daughters proceed through the K^* resonance with a pion or through annihilation of the strange quark by interaction with another kaon. Nearly one-quarter of all rescatterings occur through a variety of high mass resonances and a sizeable fraction of the rescattered K^- daughters proceed by a reaction with a nucleon into a Σ or other high mass strange baryon.

The circles in Fig. 2 display the ϕ survival probability, *i.e.* the probability that neither of the daughter kaons rescatter, as a function of m_t for the rapidity region $|y| < 1$. The probability decreases with m_t, approaching $\sim 60\%$ at the lowest m_t. As a result, the measured yield of ϕ's through the kaon channel should be lower at low m_t than that measured in the dilepton channels. The ratio of the yield of $\phi \to K^+K^-$ to $\phi \to l^+l^-$ corrected by the branching ratio should then approximately follow the circle symbols in Fig. 2 if daughter rescattering is the sole mechanism contributing to the difference.

Figs. 3 and 4 show reconstructed ϕ yields from RQMD as a function of m_t and space-time, respectively for $|y| < 1$. Fig. 3 shows $d^2N_\phi/m_t dm_t dy$ at mid rapidity for all ϕ mesons which decay in RQMD overlayed with the m_t distribution for those ϕ's whose daughters kaons do not rescatter and those ϕ's whose daughters do rescatter. The depletion of reconstructed ϕ's at low m_t results in a higher effective temperature of the ϕ meson at low m_t. The inverse slope for $0 < m_t - m_\phi < 1$ GeV of the original ϕ's is $T = 220 \pm 3$ MeV while for ϕ's observed through the kaon decay channel RQMD predicts $T = 242 \pm 4$ MeV. The extracted yields and temperatures of ϕ's should therefore be measureably different due to daughter rescattering.

The m_t dependence of the rescattering effect upon ϕ's is a reflection of the phase space freeze-out distribution of particles in heavy ion collisions. Fig. 4 shows the freeze-out distribution in time and space of the ϕ's from RQMD. The left hand figure shows the freeze out longitudinal proper time $\tau = \sqrt{t^2 - z^2}$ where t and z are the freeze-out time and z-position, while the right hand figure displays the radial freeze-out distribution. The solid line corresponds to those ϕ's whose daughters escaped unscathed from the collision, while the dashed line shows the distribution for those whose daughters did rescatter. It is clear from the figure, and intuitive, that those ϕ's with rescattered daughters predominantly decayed at

early times in the dense nuclear media, during that part of the collision of particular interest for chiral symmetry measurements.

This picture is echoed in the rapidity distributions in Fig. 5 where in the top plot we present the rapidity of (1) all ϕ's, (2) those ϕ's whose daughter kaons escape the collision zone unperturbed and (3) those ϕ's whose daughters do not escape. Here we see the approximately 25% of all ϕ's that are lost in the collision. The effect of rescattering is similar to that seen in the m_t distribution as those ϕ's closer to $y = 0$ have a larger probability of being rescattered. In the bottom half of Fig. 5 we plot the probability of survival of both daughter kaons which has a clear rapidity dependence. This dependence leads to a marginal widening of the measured $\phi \rightarrow KK$ rapidity distribution relative to that of the $\phi \rightarrow ll$ channel.

The conclusions from RQMD simulations are intuitive. Those ϕ's that decay at early times are more apt to have rescattered daughter kaons due to the amount of hadronic matter through which they must travel. Further, rescattering and pressure build-up during the collision implies that particles that freeze-out early in the collision will have a softer transverse mass distribution than those which freeze-out later [9]. We then expect that the rescattering effects at early times will be reflected in the transverse mass distribution as confirmed in RQMD.

In order to compare these observations with experimental measurements we note that RQMD only includes the imaginary part of the cross section in its calculations. While Shuryak and Thorrsen [10] have shown that the real cross section for kaons in a dense nuclear medium is much smaller than the imaginary cross section, we estimate here the maximal effect on the observed cross section expected from the inclusion of the real part.

The addition of the real cross section can, at most, rescatter or absorb all kaons from ϕ's that decay within the freeze-out volume. Shown in the bottom two plots of Fig. 4 is the point of last rescattering for kaons from RQMD. We define the freeze-out volume for kaons to be that point within which 95% of all kaons have had their last interaction, which corresponds to $\tau \leq 36.5$fm and $r \leq 20$fm. The maximal effect then of adding the real cross section to the RQMD calculation would be having all ϕ's that decay within these (τ,r)

bounds be unreconstructable and lost from the invariant multiplicity.

The square symbols in Fig. 2 show the result of making such a drastic assumption. In the lowest m_t bin approximately 25% more ϕ's are depleted than in the imaginary only calculation. Note that the inclusion of the real part of the cross section will only change the quantitative result from RQMD slightly while the qualitative shape remains the same.

C. Discussion

Recently, two experiments at the SPS studying Pb+Pb collisions with a beam energy of 158GeV/c have made preliminary reports of ϕ measurements [5–7]. Experiment NA50 [5] measured $\phi \rightarrow \mu^+\mu^-$ at mid rapidity over the transverse mass (m_t) range $1.7 < m_t < 3.2$ GeV/c^2 while experiment NA49 [6,7] reported a $\phi \rightarrow K^+K^-$ distribution also at midrapidity but for $1 < m_t < 2.2$ GeV/c^2. The reported m_t inverse slopes are strikingly different; NA50 quotes $T = 218 \pm 10$ MeV while NA49 finds $T = 305 \pm 15$ MeV.

Although, within the present accuracy, the data seem to be more consistent in the m_t range where they overlap, the extrapolated yields are significantly different. This points either towards a drastic softening of the m_t distribution with increasing m_t or distinctly different spectra reconstructed from $\phi \rightarrow KK$ and $\phi \rightarrow \mu\mu$. The latter is in qualitative agreement with the effect of rescattering of the decay kaons, depleting the low m_t region. Quantitatively RQMD predicts a 17 MeV difference of the slope, much smaller than the observed difference. The curve in Fig. 2 shows the ratio of the two extrapolated spectra, $\phi \rightarrow KK/\phi \rightarrow \mu\mu$, compared to the calculations from RQMD for the expected and maximal effect of rescattered daughter kaons. The curve is well below what could be described by even the maximal daughter rescattering and we conclude that this effect can not by itself describe the experimental data.

It is interesting to note, however, that RQMD does reproduce the observed $\phi \rightarrow KK$ rapidity distribution. The line in Fig. 5 corresponds to the experimentalists gaussian fit to their data in [7] with no renormalization on our part. This line corresponds quite nicely to the

RQMD curve for measured $\phi \to KK$ for those phi's whose daughters did not rescatter. The gaussian width and height of the distribution from RQMD ($\sigma = .96 \pm .1$, $A = 2.45 \pm .46$) are approximately consistent with the fit to the experimental data ($\sigma = 1.22 \pm .17$, $A = 2.43 \pm .15$) though the RQMD distribution is not particularly well described by a gaussian.

Comparisons of $\phi \to KK$ with $\phi \to ll$ may be very informative if the spectra are measured over the same range of m_t, with similar systematics. If the ratio of the m_t spectra has the shape characterstic of rescattering, the low m_t dip in the $\phi \to KK/ll$ ratio reflects the amount of rescattering and therefore the time spent in the dense hadronic phase. This could help to clear up uncertainties about how long the hadronic system interacts before freezing out [11,12]. Including effects of chiral symmetry restoration on kaon properties may alter these arguments, but it is unlikely that both effects will produce identical m_t dependencies.

D. Acknowledgements

We would like to thank Dr. H. Sorge for the use of the RQMD code and gratefully acknowledge helpful discussions with Dr. E. Shuryak. We further acknowledge the aid of Drs. C. Hoehne and N. Willis for aid in acquiring and interpreting the NA49 and NA50 data, respectively.

REFERENCES

[1] V. Koch, Int. J. Mod. Phys. **E6** (1997) 203; F. Karsch, Nucl. Phys **A590** (1995) 367c.

[2] D. Lissauer and E. V. Shuryak, Phys. Lett **B253** (1991) 15.

[3] D. Seibert and C. Gale, Phys. Rev **C52** (1995) 490.

[4] H. Sorge, Nucl. Phys **A630** (1998) 522c.

[5] N. Willis for the NA50 collaboration, Nucl. Phys. A 661 (1999) 534c.

[6] C. Hoehne for the NA49 collaboration, Nucl. Phys. **A661** (1999) 485c.

[7] V. Friese, PhD thesis, Universitaet Marburg (1999).

[8] Y. Akiba *et al.* (E-802 Collaboration) Phys. Rev. Lett. **76** (1996) 2021.

[9] U. A. Wiedemann and U. Heinz, Phys. Rev. C **56** (1997) 3265.

[10] E. Shuryak and V. Thorsson, Nucl. Phys. **A536** (1992) 739.

[11] R. Stock, Phys. Lett **B456** (1999) 277.

[12] M. M. Aggarwal *et al.* (WA98 Collaboration) Phys. Rev. Lett. **83**(1999) 926.

TABLES

Interaction	Percentage
$K^+\pi \to K^*$	24%
$K^+K^- \to \pi\pi$ or KK or f	26%
$K^+K^0 \to \pi\eta$ or K^+K^0	20%
K^+ High Mass Resonance $\to X$	27%
All others	3%

TABLE I. The dominant channels in the rescattering of K^+ daughters from ϕ decays in Pb+Pb collisions at SPS energies.

Interaction	Percentage
$K^-K^+ \to \pi\pi$ or $\pi\rho$ or $\pi\eta$	23%
$K^-K^0 \to \pi\eta$ or KK	10%
$K^-\pi \to K^*$ or $K\pi$	21%
$K^-n \to X$	8%
$K^-p \to X$	17%
K^- High Mass Resonance $\to X$	21%

TABLE II. The dominant channels in the rescattering of K^- daughters from ϕ decays in Pb+Pb collisions at SPS energies.

FIGURES

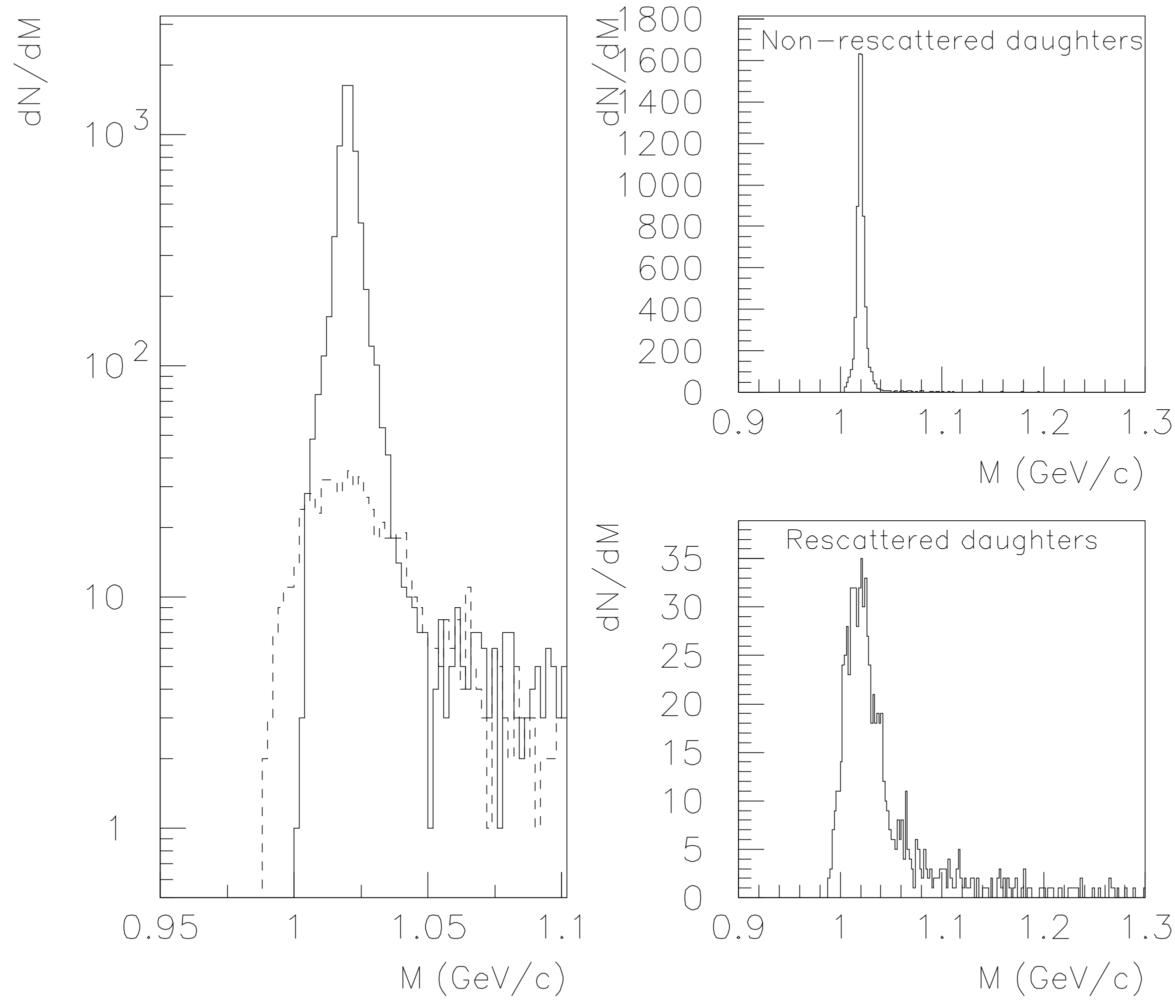

FIG. 1. Invariant mass distributions of reconstructed $\phi \rightarrow K^+K^-$ in RQMD. The top right hand figure shows the reconstructed peak for ϕ's with non-rescattered daughter kaons. The bottom right figure is for those ϕ's who had either one or both daughters rescatter before leaving the collision zone. The left hand figure shows an overlay of these two plots.

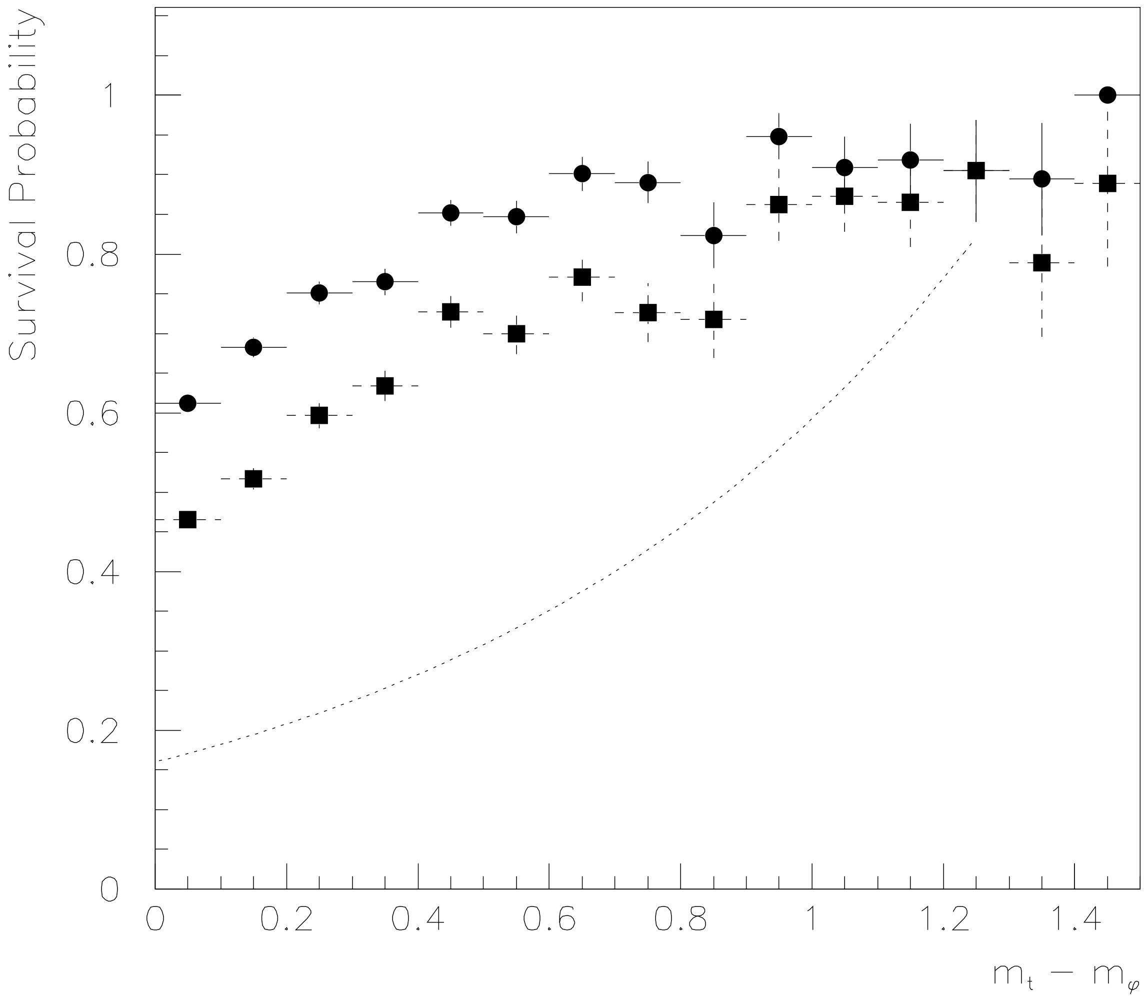

FIG. 2. The probability that a ϕ produced in RQMD that decays to two kaons will have daughters that escape the collision zone without rescattering as a function of m_t (circles) compared to experimental measurements of $\phi \rightarrow \mu\mu$ (NA50) to $\phi \rightarrow KK$ (NA49) corrected for the appropriate branching ratio [5-7] (dotted line). The squares represent the maximal possible depletion of ϕ mesons as described in the text. All points corresond to those ϕ's with rapidity $|y| < 1$.

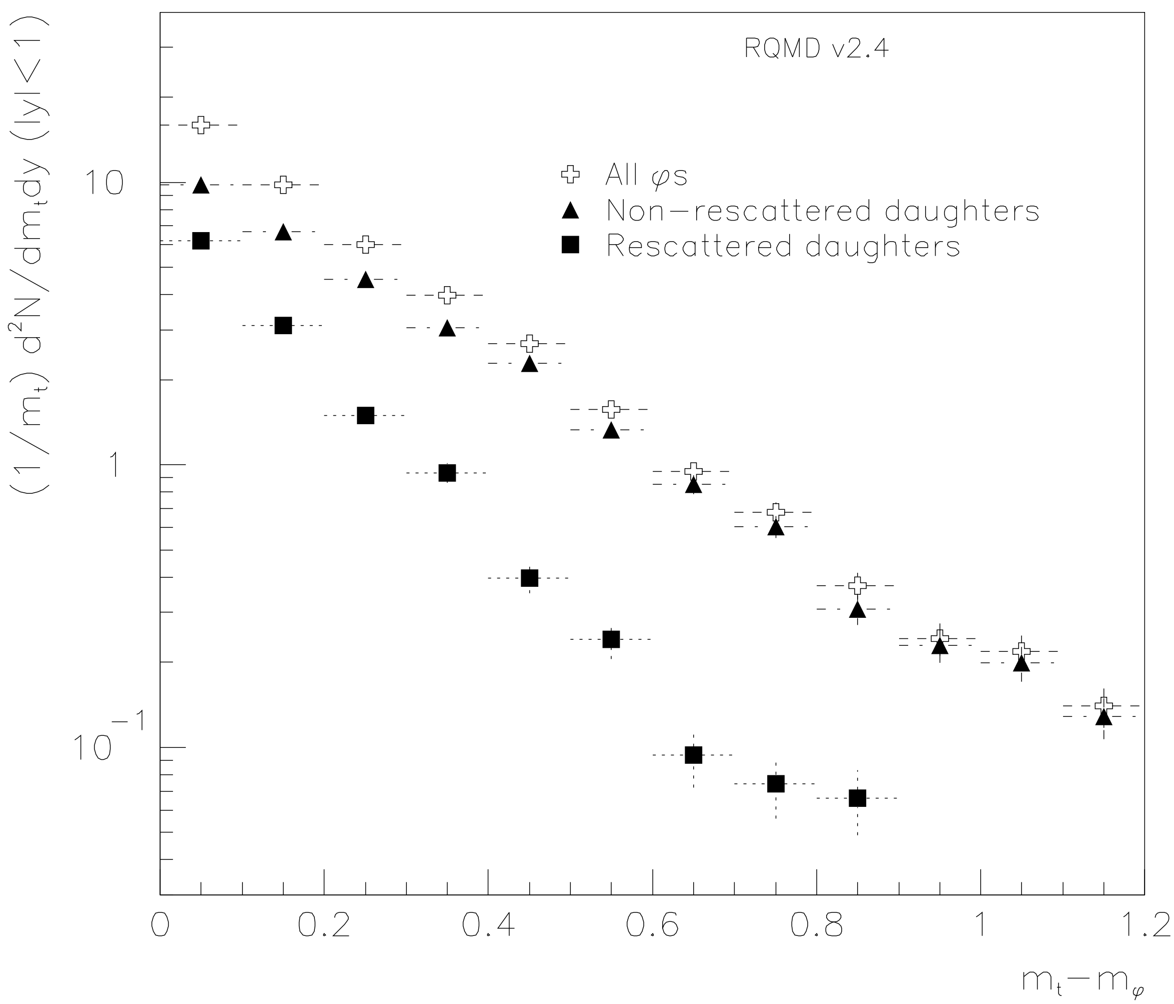

FIG. 3. The transverse multiplicity distributions of all ϕ's that decay to two kaons in RQMD (crosses), as well as those those whose daughters rescatter (squares) and those whose daughters do not rescatter (triangles). All multiplicity distributions have been corrected for the ϕ branching ratio to K^+K^-.

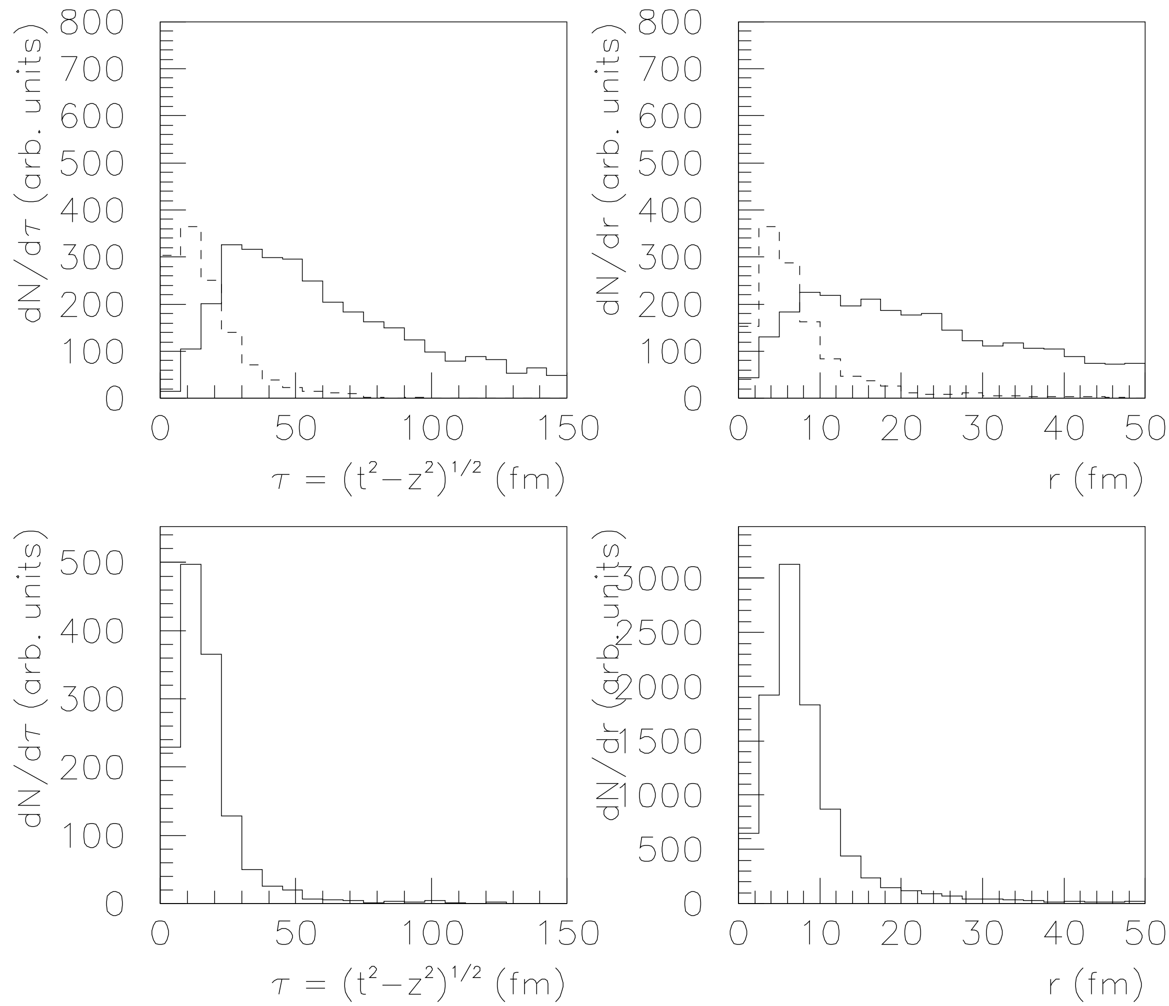

FIG. 4. The two top plots show the space time freeze out distributions for ϕ's whose daughters rescattered (dashed) as well as those whose daughters escaped the collision zone without rescattering (solid). The bottom two plots show the freeze out distribution of all kaons from Pb+Pb collisions at the SPS. τ is the longitudinal proper time $\tau^2 = t^2 - z^2$ and r is the radial position $r^2 = x^2 + y^2$.

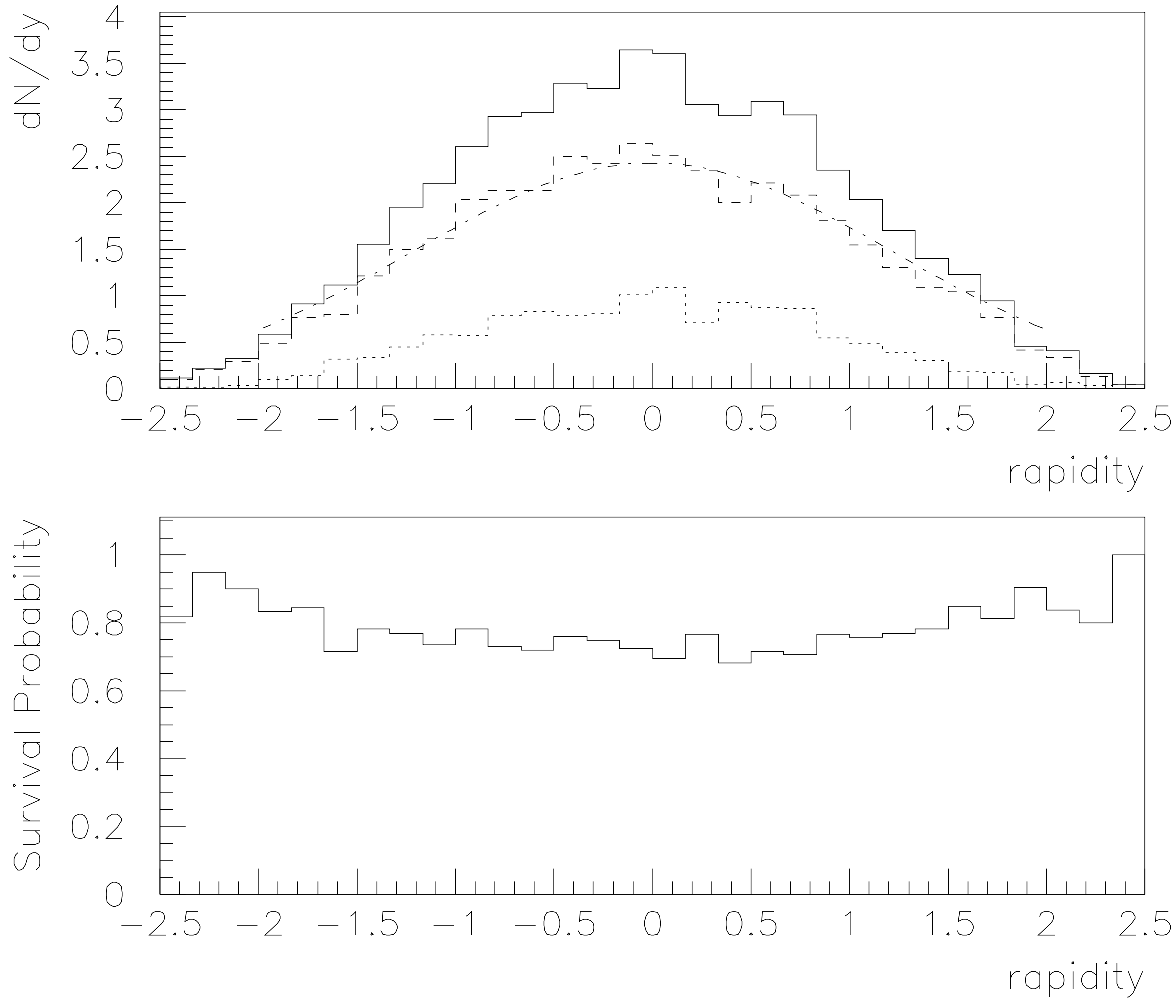

FIG. 5. Rapidity distributions of ϕ's decaying to K^+ K^- corrected for the branching ratio from Pb+Pb collisions at the SPS determined by RQMD v2.4. The top plot shows the rapidity distribution for all ϕ's (top), all ϕ's whose daughters were not rescattered or absorbed (middle), and all ϕ's whose daughter were rescattered or absorbed (bottom). The curve corresponds to a fit to the experimental data as described in the text. The bottom plot displays the survival probability as a function of rapidity.